

Are Recent Peculiar Velocity Surveys Consistent?

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Abstract. We compare the bulk flow of the SMAC sample to the predictions of popular cosmological models and to other recent large-scale peculiar velocity surveys. Both analyses account for aliasing of small-scale power due to the sparse and non-uniform sampling of the surveys. We conclude that the SMAC bulk flow is in marginal conflict with flat COBE-normalized Λ CDM models which fit the cluster abundance constraint. However, power spectra which are steeper shortward of the peak are consistent with all of the above constraints. When recent large-scale peculiar velocity surveys are compared, we conclude that all measured bulk flows (with the possible exception of that of Lauer & Postman) are consistent with each other given the errors, provided the latter allow for “cosmic covariance”. A rough estimate of the mean bulk flow of all surveys (except Lauer & Postman) is $\sim 400 \text{ km s}^{-1}$ towards $l = 270^\circ$, $b = 0^\circ$.

1. Introduction

The SMAC cluster sample (see Smith et al., this volume; Hudson et al. 1999) has a peculiar velocity of $\sim 600 \text{ km s}^{-1}$, with respect to the Cosmic Microwave Background (CMB) frame, within a depth of $\sim 12000 \text{ km s}^{-1}$. Other surveys (Willick 1999a,b, also this volume, hereafter LP10k; Lauer & Postman 1994, hereafter ACIF) have also yielded large bulk motions on similarly large scales. Taken at face value, these results appear to be in gross conflict with cosmological models. However, at the same time, other surveys (notably Dale et al. 1999, also Dale & Giovanelli this volume, hereafter SC) have found rather small bulk motions on similar scales. Because all of these surveys are quite sparse, small-scale (“internal”) flows will not completely cancel, and will act as an extra source of noise. In order to allow for these “aliasing” effects, it is necessary to account for the sparse spatial sampling and to have some idea of the expected level of the internal flows. The latter can be obtained if the power spectrum of mass fluctuations is known. To calculate these effects we will follow the methods of Kaiser (1988) and of Watkins & Feldman (1995). The purpose of

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this contribution is to address two questions. First, what bulk flow do we expect for the SMAC sample, given currently popular cosmological models. Is the SMAC result consistent with these expectations or does it demand substantial revision of the models? Second, are the various large-scale survey bulk flow statistics consistent with each other, given this extra small-scale noise?

2. SMAC vs. cosmological models

The SMAC sample consists of 56 clusters to a depth of $\sim 12000 \text{ km s}^{-1}$, and so is a rather sparse sample. The SMAC bulk flow of $630 \pm 200 \text{ km s}^{-1}$ in the CMB frame is inconsistent with zero at the 99.9% confidence level (CL). A sphere of radius 12000 km s^{-1} would be expected to have a typical (rms) bulk flow of $\sim 150 \text{ km s}^{-1}$ for a COBE-normalized Λ CDM model. Thus, naively, the SMAC bulk flow appears to be in gross conflict with the theoretical predictions. In order to compare this result with the predictions of cosmological models, however, the SMAC sample should *not* be modeled as a top-hat sphere. As first emphasized by Kaiser (1988), it is necessary to calculate the window function for the survey and multiply this by the power spectrum to obtain the expected cosmic variance.

We have calculated the window functions for each Cartesian component SMAC bulk flow following Kaiser (1988). These are plotted in the top panel of Fig. 1. Note that the window functions “ring” on small scales ($k > 0.05$). When the window function is multiplied by the power spectrum (middle panel), we obtain the contributions to the bulk flow cosmic variance as a function of scale (bottom panel). The contributions to the bulk flow statistic come from a wide range of scales, with significant contributions from scales as small as $\lambda \sim 30h^{-1} \text{ Mpc}$ ($k \sim 0.2$).

To assess the consistency with cosmological models, we compute a total covariance matrix $\mathbf{C} = \mathbf{C}_{\text{cosmic}} + \mathbf{C}_{\text{pv}}$, where the subscript “cosmic” denotes the cosmic variance part and “pv” denotes the peculiar velocity errors. For the observed SMAC bulk flow, we can then compute $\chi^2 = \mathbf{V}^T \cdot \mathbf{C}^{-1} \cdot \mathbf{V}$, where \mathbf{V} is the observed bulk flow vector. By comparing this statistic with the probability distribution for χ^2 with three degrees of freedom (corresponding to the three components of the bulk flow vector) we obtain, for a given cosmological model, the probability of observing a flow as large as we do. As the amount of fluctuation power decreases, so does the $\mathbf{C}_{\text{cosmic}}$, the cosmic variance in the bulk flow, and so χ^2 increases. This can be used to place constraints on power spectra. For example, consider the Galactic y-component of the bulk flow, which dominates the SMAC signal. For the Λ CDM model of Table 2, the expected rms cosmic value is $\sim 175 \text{ km s}^{-1}$. This is considerably larger than the cosmic rms of $\sim 85 \text{ km s}^{-1}$ which would be expected if the sphere to 12000 km s^{-1} was fully sampled, but is still quite small compared to the observed bulk flow component of 680 km s^{-1} in that direction. We conclude that this model is excluded at the 97% level. On the other hand, if we consider a CHDM model (see Table 2), the expected cosmic variance increases to 225 km s^{-1} , because of the additional power on intermediate scales (see the middle panel of Fig. 1). This model is excluded at only the 91% CL.

In a similar fashion, we can vary the parameters of a given family of models and ask which combinations yield cosmic variances which are too small compared

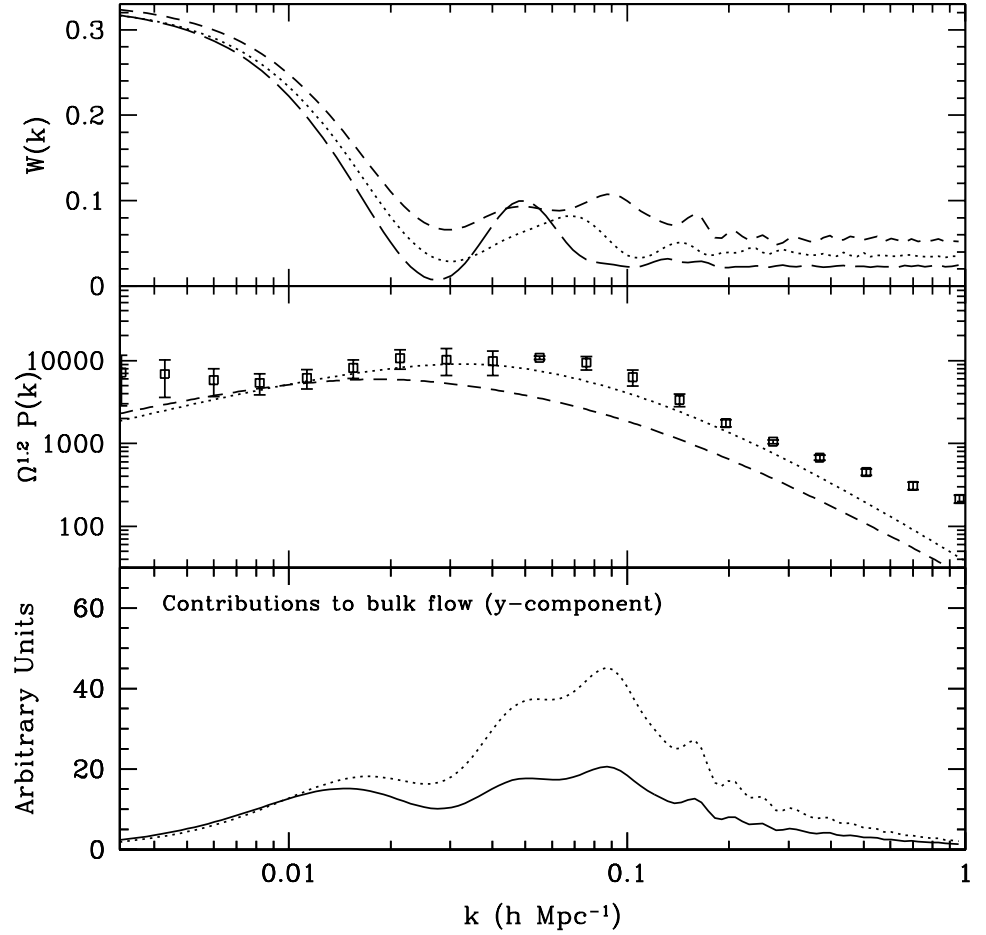


Figure 1. Top panel: Window functions for the three Galactic Cartesian coordinates. x – dotted; y – short dash; z – long dash. Middle panel: Power spectra for two models: Λ CDM (dashed); CHDM (dotted). See Table 2 for details of these models. Data points are from the APM galaxy survey (Gaztanaga & Baugh 1998). Bottom panel: the window function of the bulk flow multiplied by the power spectra (Λ CDM – dashed; CHDM – dotted). This panel shows the wide range of scales ($0.007 \lesssim k \lesssim 0.2$) that contribute to the cosmic variance of the SMAC bulk flow statistic.

to the observed SMAC bulk flow. In Fig. 2, we show the excluded regions of Ω - h parameter space for COBE-normalized flat Λ CDM models with $\Omega_b = 0.02h^{-2}$. As can be seen from Fig 2., the excluded regions are well delineated according to the combination $\Omega^{(0.53-0.13\Omega)}\sigma_8$, where σ_8 is the rms mass fluctuation in an $8 h^{-1}\text{Mpc}$ sphere. This same combination also determines the abundance of rich clusters. The SMAC result require that this combination be > 0.64 at the 95% level. This is formally inconsistent with cluster constraint ~ 0.55 (e.g. Eke et al. 1996), but is consistent with determinations of $\Omega^{0.6}\sigma_8$ from other peculiar velocity surveys (Zaroubi et al. 1997; see also Zehavi et al. in this volume). Note that, if on the other hand we adopt a power spectrum which is steeper than Λ CDM on scales smaller than the peak (e.g. CHDM) we do find consistency between the SMAC result and the cluster constraint.

This shows that, even when allowing for the aliasing effects of sparse sampling, the bulk motion of the SMAC survey is still rather too large to be comfortably accommodated by the family of Λ CDM models. Therefore, we conclude that there is evidence for excess power on scales $\sim 30 - 1200h^{-1} \text{ Mpc}$ although, at present, it is significant at the $\sim 2\sigma$ level.

3. Consistency of SMAC, SC, LP10k, ACIF and SNIa

In this section, we consider results from 5 surveys. In addition to SMAC, these are: SC, LP10k, ACIF and SNIa (Reiss et al. 1995). We have measured bulk flows for each of these surveys in a consistent way, adopting the authors' peculiar velocities and errors, but adding in quadrature an addition 'thermal' scatter of 250 km s^{-1} , to represent the scatter of individual clusters around the large-scale bulk flow. This reduces the weight of some nearby well-observed clusters such as Centaurus. For the ACIF survey, we estimate bulk flows and errors following Hudson & Ebeling (1997). The bulk flow results are given in Table 1.

Table 1. Bulk flows for different surveys

Survey	Method	N	Depth	V	<i>l</i>	<i>b</i>
SMAC	FP	56	6600	630 ± 200	260	-1
LP10k	TF	15	11100	1000 ± 438	277	27
SC	TF	63	8100	104 ± 119	300	18
SNIa	SNIa	24	4000	444 ± 194	276	-8
ACIF	BCG	119	8400	832 ± 252	349	51

The window functions of each survey are quite different, particularly on small scales. This is a reflection of the fact that all surveys react to the same large-scale structures, but the aliased contribution arising from small scales differs from one survey to another depending on the spatial sampling. We therefore expect the measured bulk flows to be correlated, but not identical, even in the absence of peculiar velocity errors. We refer to this as "cosmic covariance". Given a power spectrum, this cosmic covariance matrix can be quantified, following the method of Watkins & Feldman (1995). Specifically, we compare with zero the measured difference between the bulk flows of two surveys A and B,

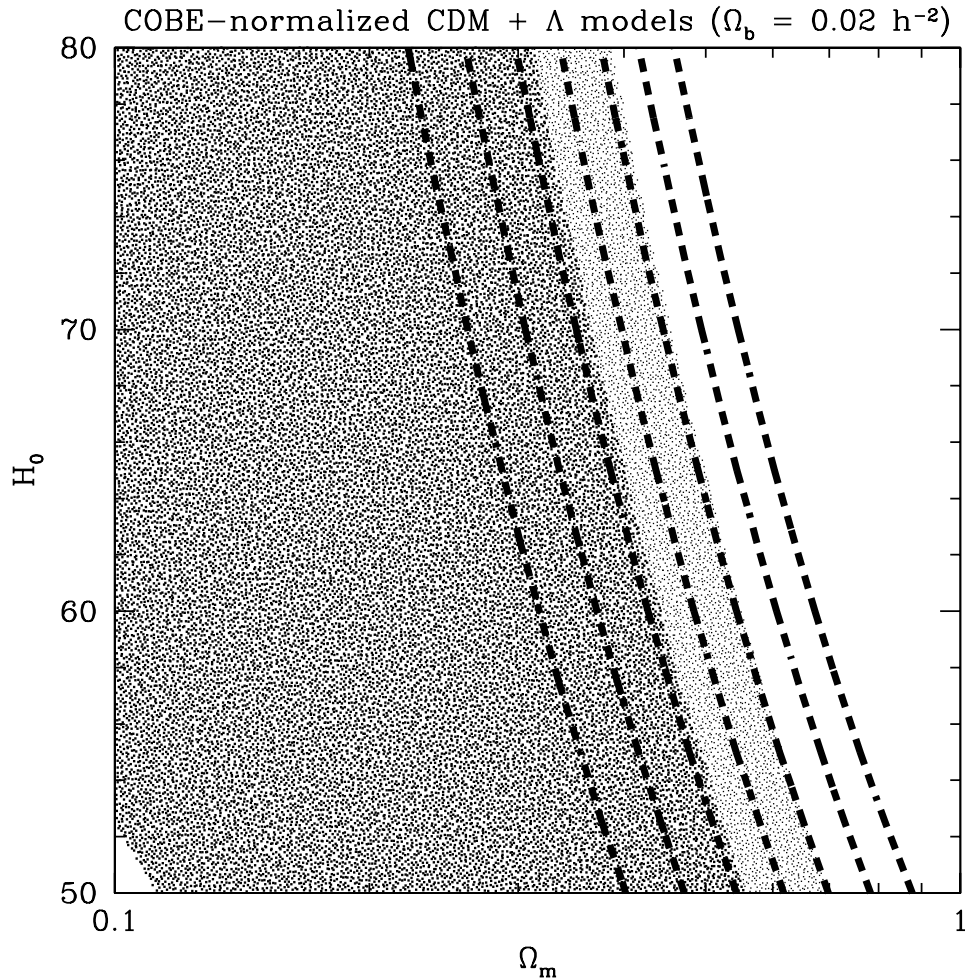


Figure 2. Constraints on Ω and H_0 for flat COBE-normalized Λ CDM models. The dark grey region indicates the parameter space excluded at better than the 95% CL by the observed SMAC bulk flow. The light grey region shows marginally excluded parameter space (between 90% and 95% CL). The dashed lines indicate combinations of $\Omega^{(0.53-0.13\Omega)}\sigma_8$ from 0.4 to 1.0 (left to right) in steps of 0.1. The cluster abundance constraint yields 0.52 (Eke et al. 1996) for this value, which is excluded at just better than 95% by the SMAC bulk flow. Note that this is a model-dependent result: for spectra which are steeper on scales shortward of the peak (e.g. CHDM) there is overlap between the cluster abundance constraint and the SMAC bulk flow.

$\mathbf{V}_A - \mathbf{V}_B$. In order to determine whether the observed difference is significant, the error analysis includes both the peculiar velocity errors and “cosmic covariance”. The latter is calculated by computing the full covariance matrix of the bulk flow components for the two surveys. This cosmic covariance term is not negligible. For most comparisons here, the expected rms difference between bulk flows in the absence of peculiar velocity errors is still $\sim 200\text{--}300 \text{ km s}^{-1}$.

In Table 2, we present a selection of comparisons between pairs of surveys (e.g. SMAC vs. ACIF and SMAC vs. SC), as well as comparisons of the type Survey A vs. “All-surveys-except A”. (The SNIa results are omitted from this table because they are consistent with all results). The table lists the probability that two surveys are consistent with the same underlying peculiar velocity field. This is done for two representative cosmological models with somewhat different shaped power spectra. If the “cosmic covariance” is neglected, one would conclude that at least two surveys (ACIF and SC) are inconsistent with the rest. However, once cosmic variance is included, there is no significant conflict between SC and the other surveys. The only survey which stands apart is the ACIF survey, and even then the difference is only marginal (significant at the 93% level).¹

Table 2. Consistency of Surveys. The table shows the probability that two surveys are consistent, with the same true velocity field, given their peculiar velocity errors (‘None’) or peculiar velocity errors *plus* cosmic covariance, assuming either Λ CDM or CHDM. Comparisons which show disagreement at greater than the 95% CL are in italics.

Surveys	‘Cosmic Covariance’		
	None	Λ CDM ^a	CHDM ^b
SMAC vs. ACIF	<i>0.020</i>	<i>0.022</i>	<i>0.027</i>
SMAC vs. SC	<i>0.025</i>	0.051	0.119
ACIF vs. SMAC+SC+LP10k+SNIa	0.058	0.062	0.068
SMAC vs. SC+LP10k+SNIa	0.630	0.657	0.704
SC vs. SMAC+LP10k+SNIa	<i>0.033</i>	0.075	0.171
LP10k vs. SMAC+SC+SNIa	0.396	0.428	0.482

^a Λ CDM: $\Omega_m = 0.35$, $H_0 = 65$, $\Omega_b = 0.047$

^bCHDM: $N_\nu = 2$, $\Omega_\nu = 0.2$, $H_0 = 50$, $\Omega_b = 0.075$

Fig 3. shows a comparison of the bulk flow components obtained by different surveys. Here the error bar includes the random errors plus the contributions

¹It is expected that if the EFAR results (Colless et al., this volume) were included in this analysis, the consistency of SC would improve but that of ACIF would become worse.

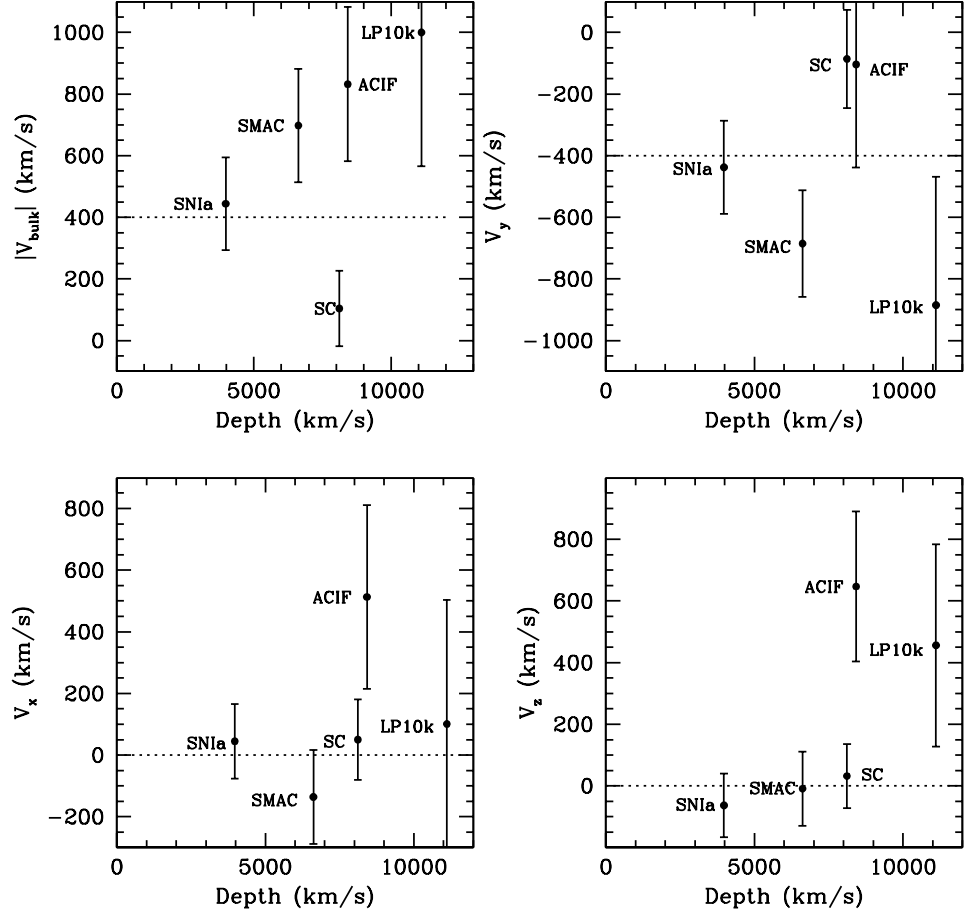


Figure 3. Bulk flow amplitude and components in Galactic Cartesian coordinates for the large-scale peculiar velocity surveys discussed in the text. The error bars include the usual peculiar velocity errors, plus an estimate of the aliased small-scale power. The dotted line shows an eyeball estimate of the mean bulk motion of all surveys (except ACIF): $\sim 400 \text{ km s}^{-1}$ towards Galactic y , $l = 270^\circ$, $b = 0^\circ$. All surveys except ACIF are consistent with this bulk motion at better than the 90% level.

of small-scale aliasing (assuming the Λ CDM model of Table 2). The dotted line shows an eyeball estimate of the mean bulk motion: $\sim 400 \text{ km s}^{-1}$ towards Galactic y , $l = 270^\circ$, $b = 0^\circ$. All surveys except ACIF are consistent with this bulk motion at better than the 90% level.

4. Summary

We have compared the bulk flow of the SMAC sample to the predictions of popular cosmological models and to other recent large-scale peculiar velocity surveys. Both analyses account for aliasing of small-scale power due to the sparse and non-uniform sampling of the surveys. We conclude that the SMAC bulk flow is in marginal conflict with flat COBE-normalized Λ CDM models which fit the cluster abundance constraint. However, power spectra which are steeper shortward of the peak are consistent with all of the above constraints. When SMAC is compared to other recent peculiar velocity surveys, we conclude that all measured bulk flows (with the possible exception of ACIF) are consistent with each other given the errors, provided the latter allow for the aliasing of small-scale power. A rough estimate of the mean bulk flow of all surveys (except ACIF) is $\sim 400 \text{ km s}^{-1}$ towards $l = 270^\circ$, $b = 0^\circ$.

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